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# Tau Physics at CDF

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# Tau Physics at CDF

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We discuss tau identification tecniques at hadron colliders, and present the measurements and the searches performed so far. We report on the first evidence of $t\bar{t}$ production in the channel containing one hadronically decaying $\tau$ lepton. We also present a search for the charged Higgs boson in the tau decay channel, as well as for the leptoquark family containing tau leptons. In addition, we underline the importance of tau physics both at present and future collider experiments.

## 1. Introduction

At $p\overline{p}$ colliders various important processes involve the emission of high–$p_T$ electron and muon leptons. Examples are $W$, $Z^\circ$ and top quark production. Collider detectors have specialized in detecting electrons and muons from these events. On the other hand, tau leptons decay predominantly into charged and neutral pions and suffer from large backgrounds from jet production, and are much more difficult to signal. However, abnormal rates of high $p_T$ taus, with respect to the Standard Model (SM) predictions, can be an important manifestation of new physics in hadron collider experiments. An example of this is the decay of top into a charged Higgs that would predominantly couple to taus. Understanding tau production at $p\overline{p}$ colliders is therefore important for several reasons:

- to check the universality of lepton couplings;
- the acceptance and sensitivity in search for processes with high–$p_T$ leptons is increased;
- and, above all, to search for new physics.

Here we present the results from the Tevatron Collider.

## 2. Tau Identification

Tau leptons decay promptly either to lighter leptons or to hadronic jets. The hadronic and leptonic Branching Ratio (BR) are respectively BR($\tau \rightarrow h\nu_\tau$) $\simeq$ 64% [1] (50% one–prong and 14% three–prong decays) and BR($\tau \rightarrow l\nu_l\nu_\tau$) $\simeq$ 36%. Here, we only consider hadronic tau decays. At the moment, the case where the taus decay to leptons cannot be distinguished experimentally from prompt electrons or muons.

The identification of hadronically decaying $\tau$'s is difficult due to the background contributed by the much more numerous quark or gluon jets. This is especially true at a hadron collider, where the hadronic activity in the final state is very abundant.

Some forms of tau identification have been implemented at the trigger level in the CDF experiment at FermiLab. These require that a cluster with a small number of calorimeter cells be found and correspond in direction to a track above a certain $p_T$ threshold. However, this trigger is not very selective. One way to circumvent triggering on the hadronic tau decay itself is triggering on other event characteristics such as missing transverse energy ($\not\!\!E_T$ ), or on other specific event topologies. So far, this method of triggering has proved to be more effective than specifically triggering on the hadronic decay of the tau lepton.

Hadronic tau decays have several characteris-

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tics that can be used to distinguish tau leptons from QCD quark or gluon jets. In general secondaries from a hadronic tau decay form a narrow collimated jet with only one charged particle track ($\approx$ 78%). Tau leptons also decay to three prongs ($\approx$ 22%). In addition, with the advent of solid state vertex detectors, large impact parameters and displaced vertices could eventually be used to enhance tau identification. The best set of variables to identify taus depends on the specific characteristics of the detector. In general both excellent tracking and calorimetry are essential.

The CDF method to identify hadronic tau decays uses both tracking and calorimeter quantities. We look for isolated tracks with large transverse momentum ($p_T$ >15 GeV/c). We use primarily the tracking isolation in a cone $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ in $(\eta, \phi)$ space around the high–$p_T$ track, as a powerful way to discriminate beween signal and background. Furthermore, using calorimeter information, we discriminate taus from electrons and muons by rejecting highly electromagnetic calorimeter clusters and minimum ionizing particles, respectively. We call this method a "track–based" $\tau$ algorithm.
Decays of $\tau$ leptons often produce neutral pions. We can thus use calorimeter informations to identify $\pi^{\circ}$'s. We can add to the previous selection a search for the photons from the decay $\pi^{\circ} \rightarrow \gamma\gamma$ in the electromagnetic shower detector. Using this method we can also extend the search to three–prongs decays of $\tau$ leptons. We call this method a "calorimeter–based" $\tau$ algorithm.

The most abundant source of high–$p_T$ leptons at hadron colliders is from $W$ bosons decays. We check the tau identification method in a data sample which is enriched in $W \rightarrow \tau\nu$ decays. Typically, a $W \rightarrow \tau\nu_\tau \rightarrow hadrons + \nu_\tau\overline{\nu}_\tau$ decay has one jet from the $\tau$, and $\not\!\!E_T$ due to the neutrinos. A monojet sample is selected by requiring one central jet with $15 < E_T < 40$ GeV, no other jet with $E_T > 7$ GeV in $|\eta| < 4.0$, and $20 < \not\!\!E_T < 40$ GeV. Figure 1a shows the track multiplicity in this sample and in a background sample of QCD jets. The latter is normalized to the monojet sample using the bins with $\geq 4$ tracks where there is a very small contribution from $W \rightarrow \tau\nu_\tau$ events. The data show a clear excess in the one-prong and three-prong bins, as expected for a sample with significant $\tau$ fraction. Figure 1b shows the track multiplicity after applying all cuts from the $\tau$ selection. The background in all bins is greatly reduced and the data agree well with the expectation from a $W \rightarrow \tau\nu_\tau$ Pythia Monte Carlo.

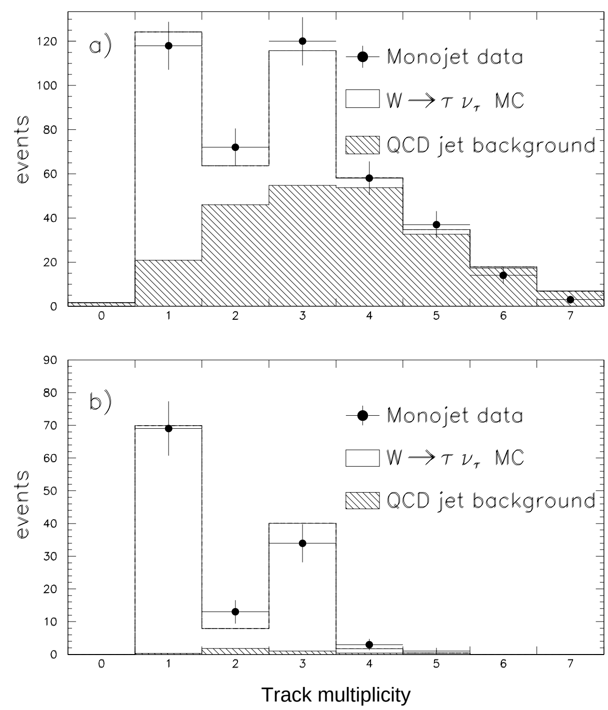


Figure 1. Track multiplicity in the monojet data sample. a) No $\tau$ ID cuts applied. b) After applying all $\tau$ ID cuts except track multiplicity.

### 3. Taus in Top Quark Decays

At the Tevatron Collider top quarks are expected to be produced primarily in pairs, $p\bar{p} \rightarrow t\bar{t}$. In the framework of the Standard Model each top quark decays into a $W$ and a $b$ quark. The final state of a $t\bar{t}$ decay therefore has two $W$ bosons and two $b$ quarks. The $t\bar{t}$ decays can be characterized by the decays of the two $W$ bosons. The *dilepton* category is represented by the case in which both $W$ bosons decay leptonically. Here we present the first evidence for top quark decays in the "tau dilepton" channel [2], where one $W$ decays into $e\nu_e$ or $\mu\nu_\mu$ and the other into the third-generation leptons, $\tau$ and $\nu_\tau$. This channel is of particular interest because the existence of a charged Higgs boson $H^\pm$ with $m_{H^\pm} < m_{top}$ could give rise to anomalous $\tau$ lepton production through the decay chain $t \to H^+ b \to \tau^+ \nu_\tau b$, which could be directly observable in this channel [3]. In the Standard Model the top BR to $Wb$ is essentially 100% and the approximate BR of $W$ to each of $e\nu_e$, $\mu\nu_\mu$, and $\tau\nu_\tau$ is 1/9, and to $q\bar{q}'$ is 6/9. Consequently, the total BR for $t\bar{t}$ into $e\tau$ and $\mu\tau$ events is 4/81, the same as for $ee$, $\mu\mu$, and $e\mu$ combined. In principle, the number of dilepton events could be doubled by including $\tau$'s. However, the 64% BR for $\tau$ decays into hadrons, decreased kinematic acceptance due to the undetected $\nu_\tau$, and a $\tau$ selection that is less efficient than the $e$ or $\mu$ selection, result in a total tau dilepton acceptance about five times smaller than that for $ee$, $\mu\mu$, and $e\mu$ events.

We report here on a search based on a $109 \pm 7\text{pb}^{-1}$ data sample collected with CDF during the Fermilab 1992–93 and 1994–95 Collider runs. The data sample used in this analysis requires high–$p_T$ inclusive lepton events that contain an electron with $E_T > 20$ GeV or a muon with $p_T > 20$ GeV/$c$ in the central region ($|\eta| < 1.0$).

Top events and background have different topologies. Dilepton events from $t\bar{t}$ decays are expected to contain two jets from $b$–decays and large missing transverse energy from the neutrinos. Due to large $M_{top}$, $t\bar{t}$ events exhibit large total transverse energy, $H_T$ [4]. Finally, the leptons must have opposite charge. The dominant background is due to a real physics process, $Z/\gamma \to \tau^+\tau^- + jets$ events. We use kinematical variables to isolate $t\bar{t}$ events by requiring:

- $N_{jets} \geq 2$, where $N_{jets}$ is the number of jets at $|\eta| < 2.0$ and $E_T > 10$ GeV;
- $H_T > 180$ GeV;
- $S_{\not{E}_T} > 3$ (GeV)$^{1/2}$, where $S_{\not{E}_T} \equiv \frac{\not{E}_T}{\sqrt{\Sigma E_T}}$ is the significance of the missing transverse energy.

In addition, one high–$p_T$ isolated track identifies the tau hadronic decay, using the method described in the previous section. The final total acceptance is very small and amounts only to about 0.1%.

We observe 4 candidate events where we expect $\sim 1$ $t\bar{t}$ event and $\sim 2$ background events (see Table 3). In three of the events we identify jets from $b$ quark decays, which supports the $t\bar{t}$ hypothesis. Two of the four candidate tau tracks show a significantly large impact parameter. Using the numbers of estimated background and observed events in Table 3 and the acceptances, we calculate the production cross section. For the calorimeter–based selection we find $\sigma_{t\bar{t}} = 10.2^{+16.3}_{-10.2}$(stat)$\pm$1.6(syst) pb, and $29.1^{+26.3}_{-18.4}$(stat)$\pm$4.7(syst) pb for the track–based selection, consistent with other measurements given the large statistical uncertainty.
In the next collider run, scheduled to start in the next millennium, each experiment at the Tevatron will record $\approx$2 fb$^{-1}$ of data. CDF expects to detect about 20 of these "tau dilepton" events. Deviations from the SM predictions will possibly become statistically significant.

| Selection | Track–based | Cal–based |
|---|---|---|
| $\tau$ fakes | 0.25±0.02 | 0.78±0.04 |
| $Z/\gamma \to \tau^+\tau^-$ | 0.89±0.28 | 1.48±0.38 |
| $WW$, $WZ$ | 0.14±0.08 | 0.24±0.10 |
| Total Background | 1.28±0.29 | 2.50±0.43 |
| expected from $t\bar{t}$ | 0.7±0.3 | 1.1±0.4 |
| Data ($b$-tagged) | 4 (3) | 4 (3) |

Table 1: The expected number of background and $t\bar{t}$ events and the observed events.

## 4. Search for Charged Higgs with Hadronic Tau Decays

The discovery of the top quark [5][6][7] at the Tevatron collider has generated a great interest in the search for new particles possibly emitted in its decay. Due to the large top quark mass a large range of mass of these daughter particles is also accessible.

Many extensions of the Standard Model have an expanded Higgs sector containing two Higgs

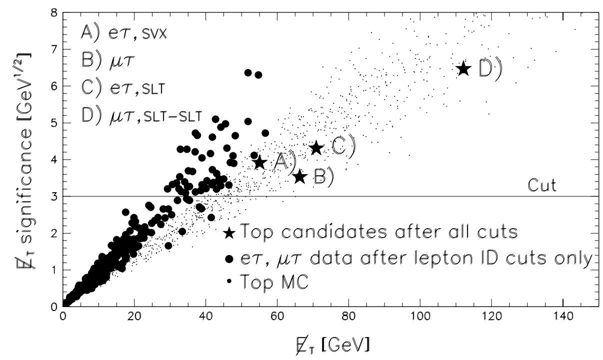


Figure 2. The distribution of $S_{\not{E}_T}$ vs $\not{E}_T$ for events with a primary lepton and a tau candidate in the data. Three of the four final candidate events (stars) have $b$–tagged jets.

doublets. The two doublets imply physical fields which include two charged Higgs particles: $H^+$ and $H^-$. If the charged Higgs exists with a mass less than that of the top quark, the top quark can decay to a charged Higgs and a b quark. This would compete with the SM decay of the top quark to a $W$ boson and a $b$ quark. In particular, the top quark decay provides a promising signature for charged Higgs boson in the region where tan$\beta \geq m_t/m_b \approx 50$ (see Fig. 3), where tan$\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. The charged Higgs would decay almost exclusively to a tau lepton, unlike the $W$, which can decay to quarks and the other leptons. Thus, an enhancement in the tau lepton channel can provide a specific signature for the Higgs boson.

At the Tevatron Collider, CDF has searched [8] for the charged Higgs boson assuming BR($H \rightarrow \tau\nu \simeq$100%). CDF observes 7 events [9], with an expected background (mostly due to fakes from QCD jets) of 7.4$\pm$2.0 events. If tan$\beta \geq$50, this analysis excludes charged Higgs boson with $M_{H^{\pm}} <$ 158 GeV/c$^2$ for a top quark mass of 175 GeV/c$^2$ and $\sigma_{t\bar{t}}$ =7.5 pb.

## 5. Search for the Third Family Leptoquark

Leptoquarks belong to a class of particles carrying both color and lepton quantum numbers which mediate transitions between quarks and leptons. Leptoquarks do not exist within the SM but appear in many SM extensions which predict a symmetry between quarks and leptons. The Tevatron with the currently highest center of mass energy in the world is in a unique position to search directly for the existence of the leptoquarks.

Assuming pair production, CDF has searched for the third generation Leptoquark (LQ3) [10] ($LQ_3\overline{LQ_3} \rightarrow \tau^+\tau^- jj$). The selection requires one of the $\tau$ leptons to decay to $e$ or $\mu$ with P$_T$ >20 GeV/c$^2$. The other $\tau$ decays hadronically. In addition, the selection requires two

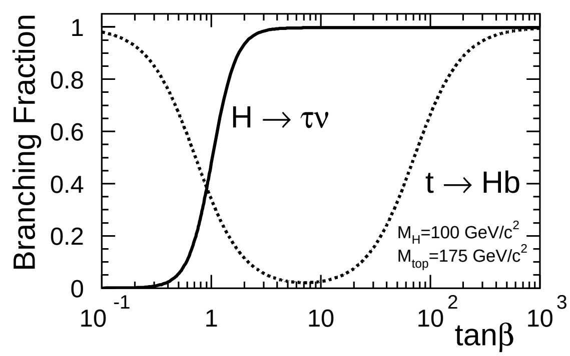


Figure 3. Branching fratio of $H \rightarrow \tau\nu$ and $t \rightarrow Hb$ as a function of tan$\beta$.

jets with E$_T$ >20 GeV. CDF observes 1 event in 110 pb$^{-1}$ of data which survives all cuts, with an estimated background of $2.4^{+1.2}_{-0.6}$ events (mostly from $Z \rightarrow \tau\tau$ +*jets*). For scalar leptoquarks we set a limit at $M_{LQ3}$ >99 GeV/c$^2$. We also consider vector leptoquarks with "anomalous chromomagnetic moments" parametrized by $k$ [11]. CDF sets a limit $M_{LQ3}$ >170 GeV/c$^2$ and $M_{LQ3}$ >225 GeV/c$^2$, for $k$=0 and $k$=1 respectively (see also [9]).

## 6. Conclusions

In conclusion, we have learned that, however difficult, tau detection is possible at hadron collider experiments. Taus can extend the sensitivity in searches for both known and "new" physics. Hadron colliders, both present and future, have an enormous discovery potential and new physics can show up as an excess of tau production. It is essential that detector upgrades and new detector designs consider tau detection as a serious matter. Vertex detectors can also help tau identification, and more experience in tau detection can still be gained at the Tevatron, to be of great interest for future collider experiments.

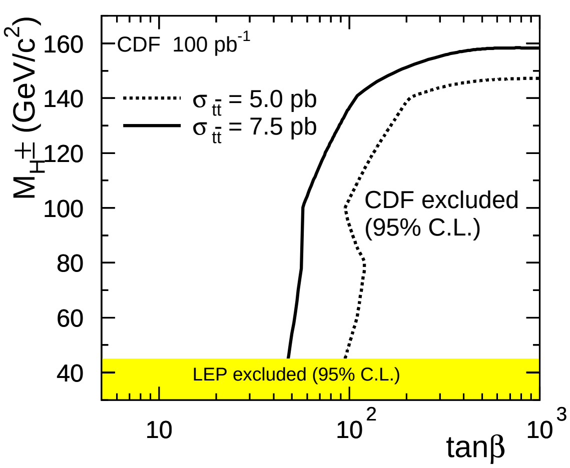


Figure 4. Charged Higgs exclusion region for $M_{top}$=175 GeV/c$^2$.

## 7. Acknowledgements


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11. $k$=1 is the "gauge theory" case where the leptoquark is a elementary gauge boson; $k$=0 is the non–gauge theory case (LQ is composite for example)